

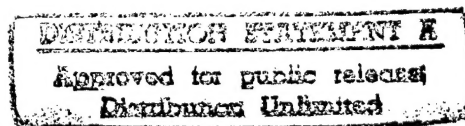
THE APPLIED MARINE RESEARCH LABORATORY  
COLLEGE OF SCIENCES  
OLD DOMINION UNIVERSITY  
NORFOLK, VIRGINIA 23529-0247

**ORIGIN AND DISPERSAL OF POTENTIALLY  
CONTAMINATED SEA ICE IN THE ARCTIC OCEAN**

By  
Dr. Dennis A. Darby, Principal Investigator  
Dr. Jens F. Bischof, Principal Investigator

Final Report  
For the period ended August, 1995 to February, 1997

Prepared for  
Program Manager/Officer ONR: 322  
Attn: Robert Edson  
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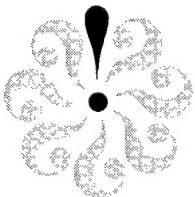
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## FINAL REPORT

# ORIGIN AND DISPERSAL OF POTENTIALLY CONTAMINATED SEA ICE IN THE ARCTIC OCEAN

### Introduction

The Arctic Ocean is unique because of its perennial ice cover and restricted water mass exchange with the other World's oceans. It is almost entirely surrounded by continents and broad shelves and possesses only one deep connection to the Norwegian and Greenland Seas, the Fram Strait. Ice is covering almost all of the Arctic Ocean during the winter months, but in the summer a large portion of the ice melts and a marginal ice-free zone opens up (Barry, 1989). The ice cover is relatively thin (2-4m) and consists of one- and multi-year old sea ice floes and pressure ridges (Koerner, 1973; Wadhams, 1981, 1983). Occasional fragments of icebergs and ice islands also are present (Clark and Hanson, 1983; Bogdanov et al. 1994; Eicken et al., 1994b; Fütterer 1994), but sea ice is the dominant ice type under the present interglacial conditions. Most sea ice forms on the shelves by freezing of seawater in contact with supercooled air during the fall (Colony and Thorndike, 1985). Depending on the location of sea ice formation, variable quantities of clastic debris can be entrained. The best conditions for sediment entrainment exist when sea ice forms during storm events (frazil-ice formation) on shallow shelves, as along the north coast of Alaska or on the broad Russian shelves. The sea-floor sediment is stirred up by a storm, and the suspended lithic particles are lifted to the surface by the newly formed ice crystals before settling. Enclosed in sea ice, the debris is then rafted away with the ice drift and drops to the sea-floor when the ice floes melt. Sediment can also directly freeze on to the bottom of an ice floe, or it can freeze to the keel of ice pileups, which can reach thicknesses of up to 30m. The preferred regions of sediment entrainment in sea ice are shallow shelves with less than 30m water depth (Reimnitz et al., 1987, 1992, 1993; Kempema et al. 1993).

Ice in the eastern Arctic Ocean is usually less than 5 years old and consistently exits into the Norwegian, Greenland, and Barents Seas (Pfirman et al. 1989, 1991). Satellite tracking of individual ice floes has shown the complexity of the short-term ice movement, which on a day-to-day scale can deviate significantly from the overall general direction (Vinje 1977, 1982). At times, ice can drift perpendicular if not opposite to the main direction of ice drift, which represents the long-term resultant of all short-term movements. Interference between the Eurasian and the Amerasian ice drift regimes probably occurs along their boundaries, possibly north of Greenland, where ice from the Beaufort Gyre can enter the Transpolar Drift and leave the Arctic Ocean via the Fram Strait and ice from the Transpolar Drift can become part of the Beaufort Gyre. This implies the possibility that ice from the eastern Arctic Ocean can enter the western part (Amerasian Basin) and contribute to sedimentation there.

The primary objective of this research was to determine whether sediment is transported by sea ice from the various Russian rivers and arctic shelf areas to the western Arctic Ocean and,

in particular, the Beaufort Sea. Knowledge of the precise sources of sediment entrainment by sea ice is important if the potential for contaminated sediment known to occur in parts of the Russian shelves to move into the Alaskan waters is to be assessed. Equally important is the quantification of the amounts of sediment in the Beaufort Sea pack ice and bottom sediment that was derived from various parts of the Russian Arctic.

### **Tasks Completed**

The origin of the lithic particles was determined by matching the composition of sea ice samples that contained sufficient coarse particles from the Beaufort Sea, the central Arctic Ocean along the track of the Arctic Ocean Section 1994 Trans-Polar Expedition, and Polarstern samples from the eastern Arctic Ocean to groups of samples with similar lithic composition from the entire Arctic data base using the classifying powers of discriminant function analysis (DFA) (Darby and Bischof, 1996). The proportions of sediment from each source were determined by matching individual Fe-oxide grain compositions from sea ice samples with adequate numbers of Fe oxide grains to groups of very similar compositions for each mineral type in source areas by DFA (Darby and Bischof, 1996). Before this could be accomplished, the Arctic source data base had to be supplemented by samples from the East Siberian Shelf, Laptev Sea, Russian rivers including the Ob and Yenesei Rivers, and the Pechora Sea.

The shape and surface textures of quartz grains were analyzed in order to find additional criteria for matching sediment to possible Russian sources and distinguishing between Eurasian and Amerasian sources. Quartz grains constitute the major portion of the sand fraction, and their shape and degree of roundness reveal the general transport history prior to entrainment in sea-ice. In addition, the clay mineral content of ice floes has been shown to be useful for identifying sources (Pfirman et al., 1996), so this was determined in 37 sea ice samples.

After the sources and the proportions from each source were established for ice floes in the various parts of the Arctic Ocean, the dispersal pathways were interpreted. All available information about past and present ice movements in the Arctic Ocean was used in conjunction with our data to generate ice trajectories and to quantify the chances for ice from Russia and the Eurasian Arctic to reach the North American Arctic.

### **Materials and Methods**

A total of 31 sea ice samples (Fig.1) were studied and analyzed for various sediment parameters. A total of 1,329 Fe oxide grain sources were determined in 23 sea ice samples using the 12 elements analyzed by electron microprobe (see Darby and Bischof, 1996 for procedures). The clay mineralogy ( $<2\mu\text{m}$ ) and silt fraction ( $2-63\mu\text{m}$ ) mineralogy was determined for 22 and 8 sea ice samples, respectively. The sources of the lithic component  $>250\mu\text{m}$  were determined for 15 sea ice samples where sufficient coarse material existed. An additional 48 samples from Russian rivers and shelf areas were analyzed for the source data set plus six new samples from

the Queen Elizabeth Islands. Lithic grain counts and over 3,000 Fe oxide grains were analyzed from these new source samples.

The mineralogy and geochemistry of opaque Fe-oxide detrital minerals ( $>45\text{-}250\mu\text{m}$ ) were analyzed for grains extracted by hand magnet and the Frantz magnetic separator set at 0.3 Amp and a  $30^\circ$  slope. The Fe-oxide grains were mounted in Epofix epoxy plugs, ground, and polished. The mineralogy of each Fe-oxide grain was optically identified by reflected light microscopy and the grain numbered on a photomicrograph for later analysis by electron microprobe for 12 element oxides ( $\text{TiO}_2$ ,  $\text{FeO}$ ,  $\text{MnO}$ ,  $\text{MgO}$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{V}_2\text{O}_5$ ,  $\text{CaO}$ ,  $\text{ZnO}$ ,  $\text{Nb}_2\text{O}_5$ , and  $\text{TaO}$ ; Darby and Bischof, 1996; Bence and Albee 1968). The electron beam size was set at half the diameter of the smaller grains analyzed in a sample to measure average compositions of heterogeneous mineral grains. This avoids time-consuming replicate analyses of each multiphase grain. Because the proportions of different phases in multiphase grains are unknown, Fe is reported as FeO instead of  $\text{FeO}$  and  $\text{Fe}_2\text{O}_3$ . The interference of the Ti  $K_\beta$  x-ray emission peak with the V  $K_\alpha$  peak was corrected by the proportional overlap method (Snetsinger et al. 1968).

The lithic and Fe-oxide data were matched between the sea-ice and the source areas using a combination of statistical methods (Darby and Bischof, 1996). First, the lithic clast composition (73 variables) in the source areas was grouped by cluster analysis (Davis 1986, SAS Institute 1989). Each cluster in which the samples had less than 0.5 average distance was assigned a source group. In cases where samples from geographically separate areas clustered together, the samples were separated into subgroups that do not cross the boundaries of major geologic provinces like the Sverdrup Basin, the Franklinian Foldbelt, Russian rivers, or geographic regions on the Russian shelves such as the Laptev Sea. The validity of the group assignments was tested with stepwise discriminant function analysis (DFA), which determines the probability of a sample belonging to its assigned group. If a sample classifies into a previously clustered group at less than 0.95 probability, it is taken out of the old group and the changed groups are re-analyzed by DFA. This procedure was repeated until all groups were unique at  $\geq 0.95$  probability of group membership and a probability of  $\geq 0.1$  that an actual member of the source group occurs as far from the source group centroid as the sample in question (Klecka 1975, Darby 1990). This second probability, herein referred to as the similarity probability, prevents samples from being forced into a group because the group is more similar to the sample than any other group under consideration, when in actuality the lithic sample should be grouped differently or left as an outlier group by itself.

In a second step, the pack ice and Beaufort Sea bottom sediment data were matched to the source area data with DFA, resulting in certain probabilities for each ice sample to belong to a previously established source group. DFA is the preferred multivariate statistic because it is insensitive to closed data or correlated variables unless they are perfectly correlated, and it provides probabilities of group membership (Klecka 1980). The highest correlation coefficient between any variables in previously analyzed source areas was -0.8 for quartz and carbonates.

The procedure for grouping and matching the opaque Fe-oxide minerals was similar except that individual grains are matched to source areas and not the entire sample. Each of the nine detrital Fe-oxide mineral types (fresh and altered ilmenite, titanomagnetite, magnetite, magnetite with inclusions, titanohematite, ferrohematite, hematite, and chromite) found in the samples from each source area were clustered separately using the standardized chemical content of individual grains. The clustered groups were tested by step-wise DFA as were the lithics. Each Fe-oxide mineral type was treated separately. All Fe-oxide grains from pack ice or Beaufort Sea bottom samples were classified into their proper sources by the same DFA procedure used to test the source group membership. Grains that did not fulfill the probability criteria of group membership and similarity were considered as originating from unknown sources. From past experience, even a tightly clustered group of source Fe-oxide grain compositions can have similarity probabilities as low as 0.1 and group membership probabilities of  $>0.95$ . When grains from the Arctic Ocean are matched to source groups from the rivers along the U.S. east coast (see Darby, 1990 for sample locations), more than 40% match with membership probabilities of  $>0.95$ , but only about 10-13% of these grains have similarity probabilities  $>0.1$ . The use of both of these probabilities provides much greater insurance against errors of misclassification than membership probability alone.

## Results

The sea ice clay and silt mineralogy are generally different for samples taken from near the Russian shelves as opposed to samples from the central Arctic Ocean (Fig. 2 and 3). The sea ice samples from the Laptev Sea and Barents Sea near Svalbard contain much higher smectite, kaolinite, and feldspar and less illite, dolomite, and calcite than the central Arctic Ocean or Alaskan shelf samples. Still the mineralogy is not always clearly distinctive for individual samples because some Alaskan shelf and central Arctic Ocean sea ice contains high smectite, kaolinite, and feldspar and some Laptev Sea samples contain 6% dolomite in the silt fraction.

The lithic grain type percentage data was used to determine the most probable source (i.e., the source area most similar in composition to the sample in question) (Table 1).

Table 1. Lithic source matches at >0.95 probability for sea ice samples. Only samples with sufficient coarse grains could be used.

SAMPLE	MATCHED SOURCE (>0.95 PROB.)
PS89-18	W. Victoria Island
ARK-IX-225-1	E. Siberian Sea + E. Laptev Sea
AOS94-207-1	Mackenzie Delta
AOS94-215-E3	E. Siberian Sea
AOS94-215-1	W. Banks Island
AOS94-226-1	?
AOS94-227-1	E. Siberian Sea
71-APB-15	Queen Elizabeth Islands + Alaskan Shelf
72-APB-18	W. Banks Island
PS89-5b	W. Victoria Island
93-230-1-1b	E. Siberian Sea (Kolyma R.)
93-230-1-1a	Alaskan Shelf
72-APB-54	W. Ellesmere Island ?
PS89-12	Wellington Channel - Barrow Strait



The Fe oxide grain matches are shown in Figure 1 along with the dispersal trajectories to show the net transport of sea ice and not the latest drift path. For example, if a sea ice sample contained Fe oxide grains from several sources, then the dominant source is shown as the origin of the dispersal and the trajectory is shown moving close to the other sources present. If sources were from Russian and Canadian or Alaskan sources, as was often the case, then two paths are shown, both traversing the Chukchi Shelf before ending at the sample site because this is the most probable area for the immediate entrainment of detritus from these sources. This important potential source area needs to be studied with many bottom samples in order to test this hypothesis.

The hypothesized drift tracks are currently being compared to satellite back trajectories. This will provide additional information on the last entrainment source area and net dispersal of sea ice sediment in the Arctic Ocean.

### **Important Findings and Conclusions**

All of the sea ice samples contained Fe oxide grains from several sources. Even the lithic particles could not be matched to sources with identical compositions suggesting that more than one source area may have contributed coarse material. This probably indicates that the exact area where sea ice last entrained bottom sediment was not included in our source area samples. The dominant sources for the Fe oxide grains in sea ice samples with more than 25 Fe oxide grains were (in order of importance): the East Laptev Sea (source 18, Fig. 1), Banks & Victoria Islands (source 8), the East Siberian Shelf (especially source areas 20 & 21), and the Alaskan Shelf (source 13) (Fig. 4). Multiple sources for every sea ice sample suggest that sea ice is depositing Fe oxide grains from primary sources onto other shelves such as the Chukchi Shelf from where it is entrained by the sea ice sampled here. This is direct evidence that sea ice has a major role in both the erosion and deposition of sediment on Arctic shelves. Alternatively, multiple sources could be obtained by sequential entrainment at several different locations. This would have to occur under the pack ice with currents instead of waves stirring-up the sand.

Net sea ice drift pathways appear more complex than would be predicted by the generally accepted surface currents. The presence of sea ice samples from the Alaskan Shelf and the western Arctic Ocean with Fe oxide grains from the Laptev Sea indicates that Russian shelf sediment is transported into the American shelf waters. The general absence of Laptev Sea Fe oxide grains on the Canadian shelf areas suggests that the sea ice transport from the Laptev Sea does not move east across the Lomonosov Ridge area and then into the Beaufort Gyre but instead moves counter to the Beaufort Gyre and general Trans Polar Drift. Sea ice probably is transported eastward from the Laptev Sea to the East Siberian Sea before being entrained by sea ice and transported into the western part of the Beaufort Gyre (Fig. 1). The sea ice samples collected from near the Laptev Sea contain significant amounts of Fe oxide grains from Canadian sources, especially Banks Island. Thus sea ice from the Beaufort Gyre is transported into Russian shelf areas also.

## Impact on Education

During the course of this project five graduate students (all masters degree candidates) and three undergraduate geology majors were supported. Two of the graduate students have finished their masters degrees and two are to finish within the next six months. The graduate students include: Steven Marshall, Steven Herman, Gita Dunhill, Vladimir Ispolatov (graduated), and Duan Li (graduated). The undergraduates include Brian Burdette, Shonia Becraft, and Marcella Ripich. Three of these students were female and one was Asian. All of the students gained valuable experience working on this project including training for two of them on the ETEC electron microprobe. All students were trained in sample preparation, polishing grain mounts, and microscopy. Rarely do students at this stage in their education get experience on sophisticated equipment such as the electron microprobe and reflected-light microscopy.

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**Map of Arctic Ocean and Source sample locations**

■ grab sample  
 ● box or piston  
 ▼ land sample  
 x sea ice sample

18 source area

200 0 200 400 600 800 1000  
KILOMETERS

GREENLAND  
ALASKA  
ICELAND  
Kara Sea

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

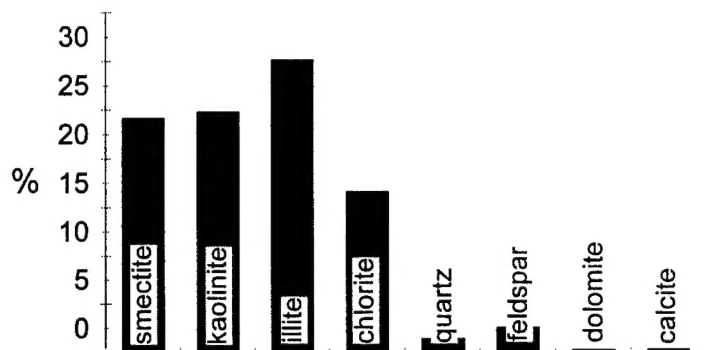
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AOS220-1  
AOS215-1  
AOS214-1  
AOS212-2  
AOS207-1  
AOS218-1  
AOS235-1  
AR94-15  
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Figure 1. Source samples and sea ice samples for Fe oxide grain source matches. Drift tracks show the net drift based on the dominant sources for each sea ice sediment sample.



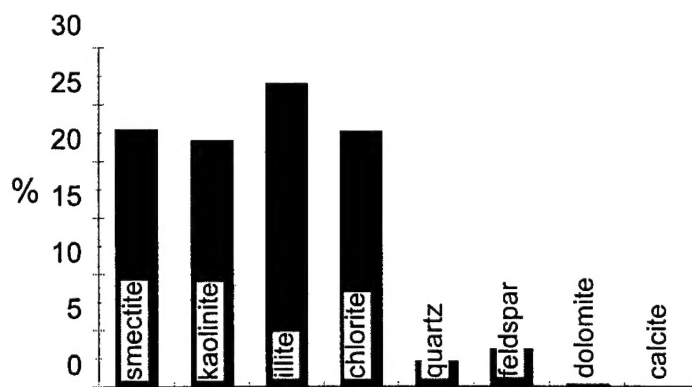
## LAPTEV SEA

sea ice sediment <2 microns



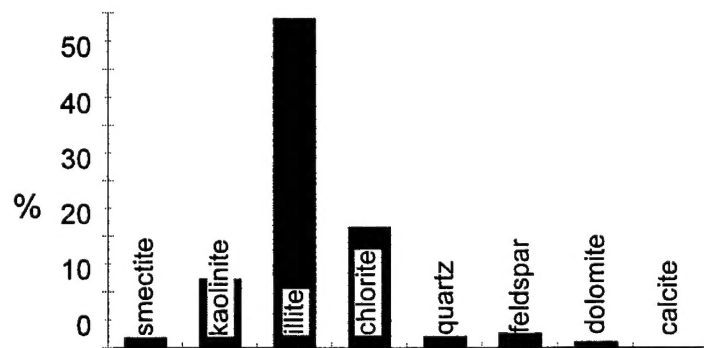
## SVALBARD SHELF

sea ice sediment <2 microns



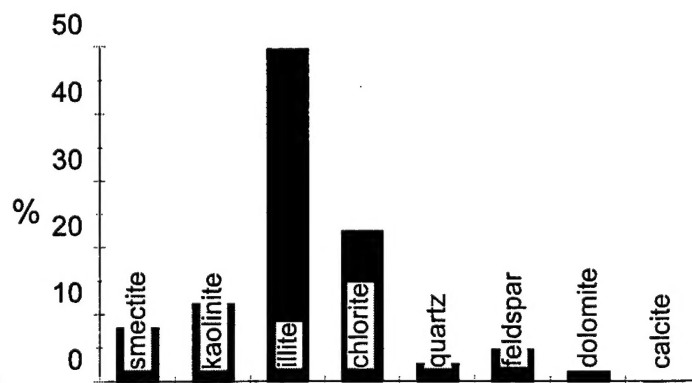
## AOS'94 W. LONG.

sea ice sediment <2 microns



## AOS'94 E. LONG.

sea ice sediment <2 microns



## ALASKAN SHELF

sea ice sediment <2 microns

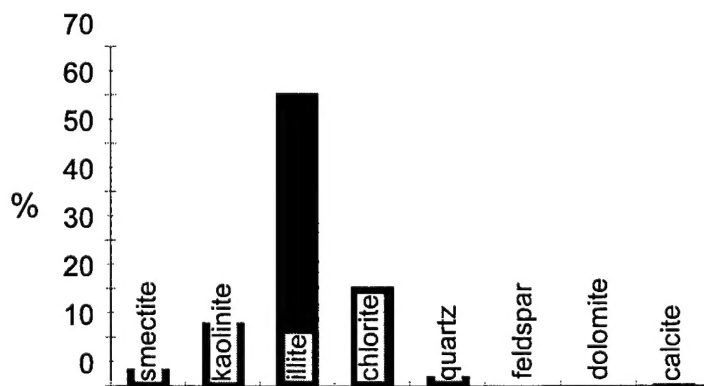
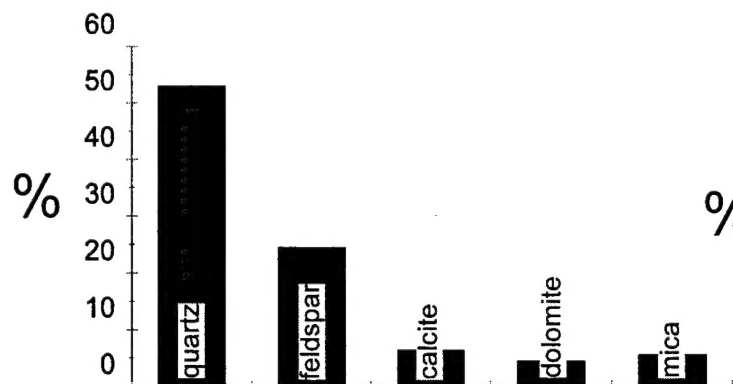


Figure 2. Average sea ice sediment mineralogy in the clay fraction for different Arctic areas. The smectite and kaolinite are significantly higher near the Russian shelves.

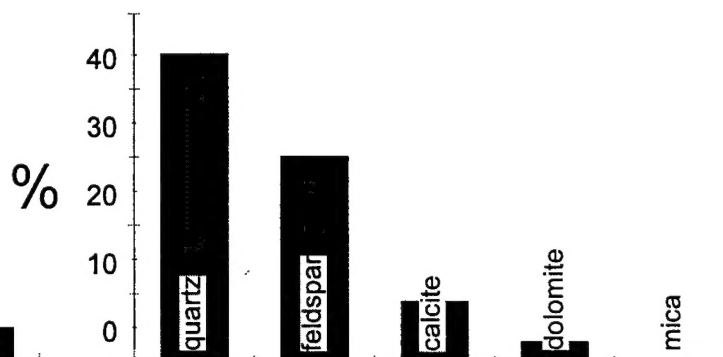
## LAPTEV SEA

sea ice sediment 2-63 microns



## SVALBARD SHELF

sea ice sediment 2-63 microns



## ALASKA SHELF

sea ice sediment 2-63 microns

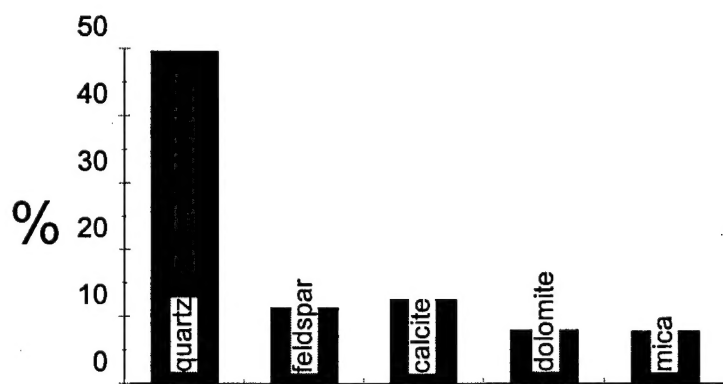
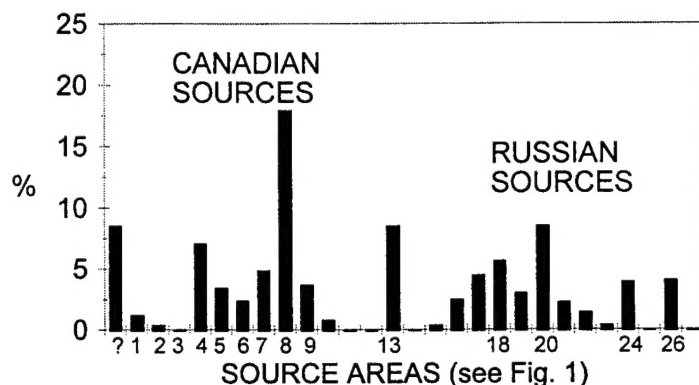


Figure 3. Average silt mineralogy of sea ice samples from different areas in the Arctic Ocean. Note the similar dolomite percentages on the Russian shelves and Alaskan Shelf despite the absence of a known source in Russia.

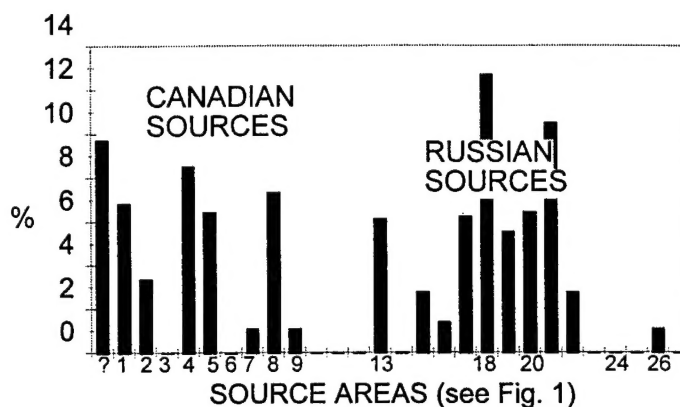
## LAPTEV SEA

Avg. Fe Oxide Sources for Sea Ice



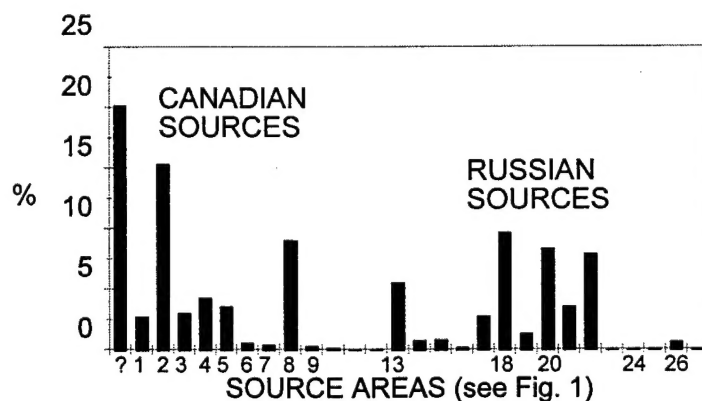
## SVALBARD SHELF

Avg. Fe Oxide Sources for Sea Ice



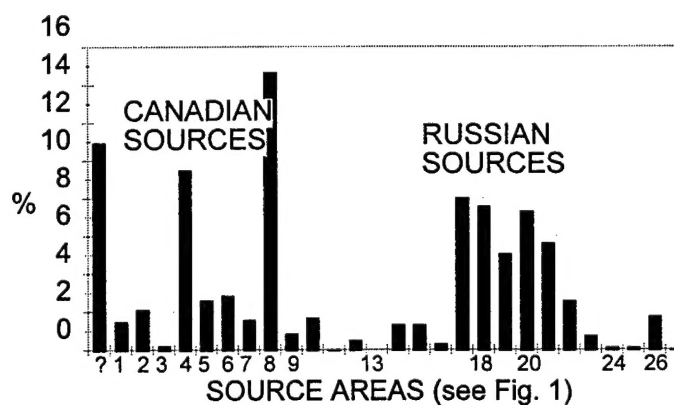
## AOS '94 W. LONG

Avg. Fe Ox Sources for Sea Ice



## AOS '94 E. LONG.

Avg. Fe Oxide Sources for Sea Ice



## ALASKAN SHELF

Avg. Fe Oxide Sources for Sea Ice

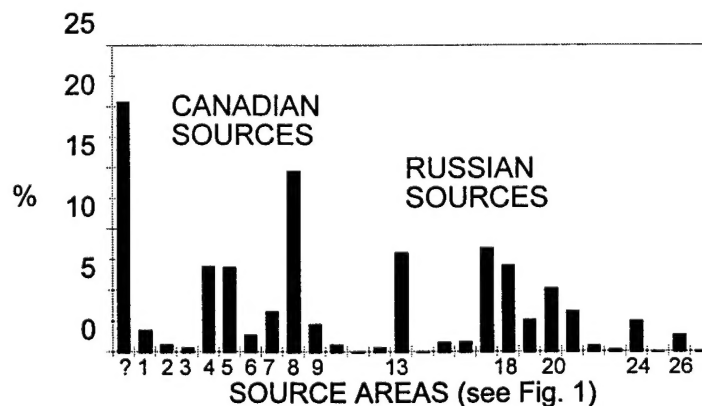


Figure 4. Average Fe oxide grain percentages from Arctic source areas defined in Figure 1 for sea ice samples from different areas of the Arctic Ocean. The dominant source areas are Banks Island (8), Ellef Ringnes Island (4), the Laptev Sea (17 and 18), the Alaskan Shelf (13), and the E. Siberian Shelf (19-23).